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THE DETECTION OF PHOTOSPHERIC X-RAY PULSATIONS FROM PG 1159 – 035 WITH *EXOSAT*

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ABSTRACT

We report the detection of soft X-ray pulsations from the hot, helium-rich, degenerate object, PG 1159 – 035. These observations, obtained with the Low Energy (LE) experiment on *EXOSAT*, show the presence of large-amplitude soft X-ray (44–150 Å) pulsations analogous to several of the low-amplitude, nonradial, *g*-mode pulsations which are observed in the optical. These soft X-ray pulsations, with periods of 516 s, 524 s, and 539 s, arise from the photosphere of PG 1159 – 035 and constitute the first observations of stellar atmospheric pulsational phenomena in the X-ray band.

Subject headings: stars: pulsation — stars: white dwarfs — X-rays: sources

I. INTRODUCTION

PG 1159 – 035 is the prototype and brightest member of a newly recognized spectroscopic class of helium-rich degenerate objects (Wesemael, Green, and Liebert 1985). The feature which characterizes all seven known members of this class of stars is a broad, shallow absorption trough of He II λ4686 blended with the several transitions of C IV, C III, and N III. A second spectral characteristic shared by four additional, possibly related, objects is the presence of O VI transitions seen in the optical, most prominently at λ3434. Frequently, sharp self-reversed emission components are present in many of the optical absorption features. The O VI features, in addition to emphasizing the high effective temperature of these objects, are seen as evidence that these stars are transitional evolutionary states between the "O VI" central stars of planetary nebulae and the hottest D0 white dwarfs (Sion, Liebert, and Starrfield 1985). The atmospheric composition of PG 1159 objects is not well determined. However, from the lack of H I Balmer lines and the presence of He II λ4686, Wesemael, Green, and Liebert (1985) find He/H > 1. CNO metals are clearly also present, but their abundance is not known.

Photometrically, four of the PG 1159 objects are known to exhibit complex low-amplitude pulsational behavior. The first evidence of such activity was observed in PG 1159 – 035 by McGraw *et al.* (1979). A detailed, long-term analysis of PG 1159 – 035 (Winget *et al.* 1985) has identified at least eight nonradial *g*-mode pulsations in this star with periods from 390 to 832 s and fractional semiamplitudes of from 0.0018 to 0.0085. From their apparent relationship to central stars and the hottest most recently evolved white dwarfs, PG 1159 objects are expected to be in a state of rapid thermal evolution on time scales short enough to be observable as changes in their pulsation periods. Indeed such a change has been observed in the 516 s period of PG 1159 – 035 (Winget *et al.* 1985).

As in the cooler ZZ Ceti DA white dwarfs, the optical pulsations observed in PG 1159 variables are primarily a temperature effect due to the change of modal temperature patterns over the surface of the star. Several lines of evidence suggest that *large-amplitude* pulsational activity ought to be observable in the soft X-ray fluxes from PG 1159 objects. First, several planetary nebulae, including the O VI central star of NGC 246, were detected in the soft X-ray band by *Einstein* (Vedder and Clarke 1985). In addition, PG 1159 – 035 itself was observed as an *Einstein* soft X-ray source (J. T. McGraw, private communication). Thus, if such soft X-rays are photospheric, as they are in hot DA white dwarfs, then PG 1159 objects are hot enough to have significant flux shortward of the He II Lyman edge at 228 Å. At the same time they are not so distant as to be obscured by the large soft X-ray absorption cross section of the interstellar medium. Second, while optical pulsations occur on the Rayleigh-Jeans tail, the soft X-ray pulsations occur on the steep Planck portion of the energy distribution. Therefore, the modest

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TABLE 1

EXOSAT AND OPTICAL OBSERVATIONS

A. *EXOSAT* Observations

Date	Filter	HJED	Duration (s)	Counts s^{-1}
1984 Jun 15	3000 Å Lex	2,445,867.10704	5,600	0.041 ± 0.004
	Al-P	2,445,867.17185	8,000	< 0.0015 (3σ)
1985 May 20 ...	3000 Å Lex	2,446,206.20908	60,322	0.044 ± 0.001
	Al-P	2,446,206.90726	4,100	< 0.0028 (3σ)

B. Simultaneous Optical

Date	HJED	Duration (s)
1985 May 21	2,446,206.65949	13,720

temperature variations (1%–2%) which produce low-amplitude pulsations in the optical will yield large, easily observable, flux modulations in the soft X-ray.

II. OBSERVATIONS

Initial observations of PG 1159−035 were performed in 1984 with the LE detector on *EXOSAT* (see de Korte *et al.* 1981). These observations provided tentative evidence of soft X-ray variability in the frequency range previously detected in the optical. Due, however, to the complex photometric behavior of PG 1159−035, it is not possible with this brief initial *EXOSAT* observation to unambiguously associate the variations with any individual optical model. Subsequently, a longer duration *EXOSAT* observation was performed in 1985 in conjunction with simultaneous high-speed, optical photometry. During both the 1984 and 1985 observations, PG 1159−035 was detected in the 3000 Å lexan filter (44–150 Å), but not in the softer aluminum-parylene (Al-P, 165–240 Å) filter. In Table 1 we provide the date, epoch, duration, filter and mean *EXOSAT* count rate for both observations. These rates do not differ significantly between the 1984 and 1985 observations.

Also included in Table 1 is the epoch and duration of the simultaneous optical photometry, obtained by one of us (A. D. G.). PG 1159−035 was observed optically with the Steward Observatory 61 inch (1.5 m) telescope. It and a nearby comparison star (235″ N and 25″ W) were observed simultaneously with the UALR two-star photometer. No filters were used with the blue-sensitive bialkali photocathode in order to increase photomultiplier tube count rates. The effective wavelength of the photomultiplier tube–atmosphere combination is slightly bluer than Johnson *B* with a peak response occurring between 3700 and 4000 Å. The data were reduced by the methods described by Grauer and Bond (1981). The data acquisition computer's time base was accurately calibrated by comparing it with WWV at regular intervals.

Figure 1 shows the portion of the *EXOSAT* data which coincides with the simultaneous optical data. These data are binned into 40 s intervals in order to obtain a minimum source count rate of ~ 1 event per time bin. A mean background correction, based on the total number of counts, was then applied. A sequence of 1508 of these bins and the times corresponding to the beginning of each interval constitute the observed *EXOSAT* time series. Compared with the optical time series, the *EXOSAT* data have a low signal-to-noise ratio; however, subtle correlations are still evident between the X-ray and optical data.

A region of the power spectrum of the entire 1985 *EXOSAT* data set is shown in Figure 2. Three strong peaks are present, corresponding to confidence levels above 99%. Although we display only a portion of the power spectrum here, an examination of the remainder shows no additional peaks at this level of significance. A simulation of PG 1159−035 X-ray data, using Poission count statistics, has been performed including intensity modulations at the observed periods. This has shown that the relative pulsation amplitudes, obtained by folding the data with respect to the observed periods, are consistent with the levels of the peaks observed in the power spectrum and demonstrates that 99% is an acceptable confidence limit.

Of the three largest peaks (see Table 2), two correspond to pulsational modes previously identified in optical power spectra of PG 1159−035 (Winget *et al.* 1985): the 516 ± 1 s peak and the 540 ± 1 s peak. In addition, a new peak appears at 524 ± 1 s, with an amplitude comparable to those of the 516 s and 540 s peaks. This peak is not found in the optical data from 1979 to 1984 of Winget *et al.* (1985), with a very good semiamplitude limit of $< 10^{-3}$. This peak, however, *does appear* in the extensive optical data set obtained during 1985 March through May (Kepler *et al.* 1986), and so the values of its optical period and amplitude have also been included in Table 2.

III. DISCUSSION

In this *Letter* we confine our discussion to the three modes present in *both* the *EXOSAT* and optical data. A more detailed comparison of the correspondences between the two data sets, such as the presence of additional modes and pulsational phase relationships, will be presented elsewhere (Kepler *et al.* 1986). In Table 2 we compare the periods, fractional semiamplitudes, and amplitude ratios obtained from the *EXOSAT* and optical data. The fractional semiamplitudes in Table 2 are determined from a linear least-squares fit to the data, which assumes the tabulated periods. As can be seen from Table 2, the periods of the three modes correspond to

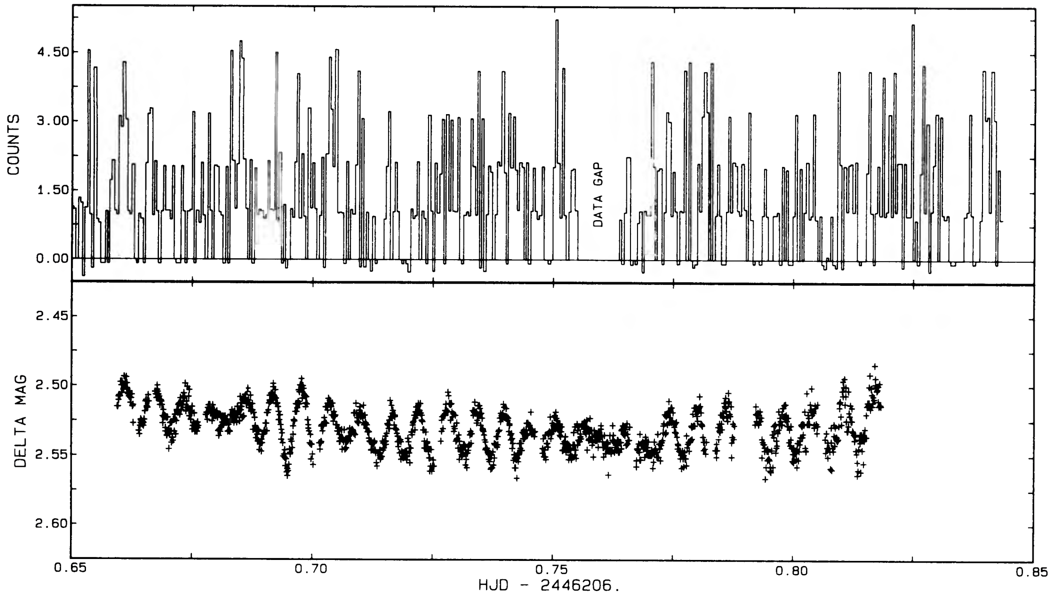

FIG. 1.—A comparison of the *EXOSAT* and optical light curves for PG 1159 − 035. The *EXOSAT* data (*upper panel*) shown here corresponds to that portion of the 1985 observation which is simultaneous with the optical observations (*lower panel*). The *EXOSAT* counts corresponds to background-subtracted counts in 40 s bins and thus are not necessarily precise integers. The optical light curve is expressed as a relative magnitude sampled at 10 s intervals.

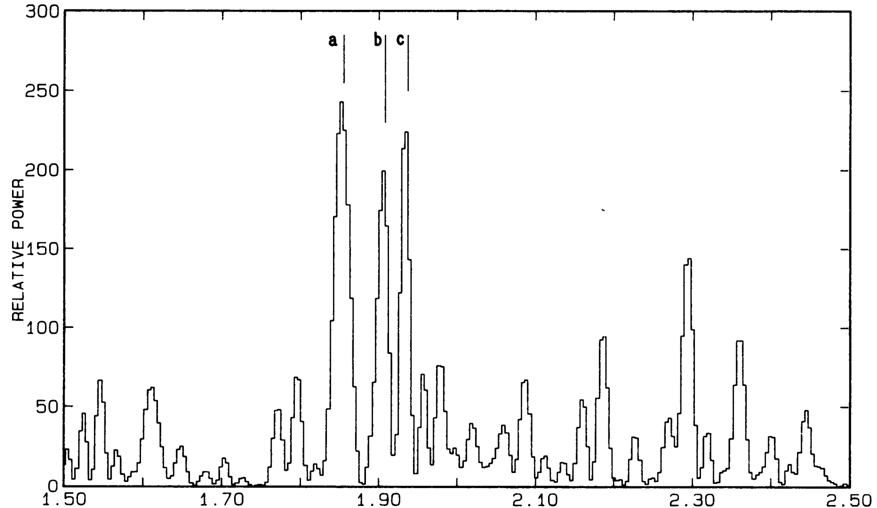

FIG. 2.—A power spectrum of the entire 16 hr *EXOSAT* time series showing frequencies in the vicinity of the three pulsation periods discussed in the text. The lines designated a, b, and c correspond to the locations of the optical periods of 539, 524, and 516 s.

within their mutual uncertainties. The most striking difference between the X-ray and optical pulsations is in their relative amplitudes. The X-ray amplitudes are 20 to 30 times larger than optical amplitudes. As has been discussed in Winget *et al.* (1985), only the 516 s mode is known to be stable and the possibility exists that the other modes are inherently unstable, or at best consist of unresolved components with a beat period of order the run length (60,000 s) or longer, causing apparent changes in their amplitudes. Hence, the apparent difference in amplitude ratio between the modes at 516 s and 540 s and the mode at 524 s is probably not significant, since it is based on a comparison of data which were not obtained simultaneously. In any event, the large X-ray–to–optical amplitude ratios offer the obvious possibility of obtaining a temperature estimate for PG 1159 − 035, which is independent of absolute calibration to first approximation. Such analysis should however be approached with caution as the following example illustrates. For a blackbody energy distribution the temperature, T, and the semiamplitude of the variation in T, ΔT, can be uniquely determined from the observed semiamplitudes of the flux variations at two separate wavelengths. Assigning effective wavelengths of 100 Å to the *EXOSAT* fluxes and 4330 Å to the optical (B band), we obtain a $T \pm \Delta T$ of

TABLE 2

PULSATION MODES PRESENT IN BOTH SOFT X-RAY AND OPTICAL

Period (s): *EXOSAT*; Optical	Fractional Semi-amplitude	Confidence Level[a]	X-Ray-to-Optical Amplitude ratio
516 ± 1;	0.15 ± 0.03	99.3%	16 ± 3
516.0269 ± 0.0006[b]	0.0092 ± 0.0005		
524 ± 1;	0.16 ± 0.03	99.4	31 ± 6
523.93 ± 0.04[c]	0.0052 ± 0.0003		
540 ± 1;	0.17 ± 0.03	99.7	20 ± 4
539 ± 1[b]	0.0083 ± 0.0005		

[a] Estimated from height of each peak above the mean power.
[b] From Winget *et al.* 1985.
[c] From Kepler *et al.* 1986.

72,000 K ± 540 K for 516 s amplitudes of the mode in Table 2. However, on the basis of the observed intensity of the soft X-rays, the far-UV energy distribution, and the presence of ions such as O VI, the true effective temperature of PG 1159−035 is clearly in excess of 100,000 K. As has been pointed out by Shipman (1979), blackbodies are generally poor approximations to the emergent soft X-ray and extreme UV flux from very hot stellar atmospheres. Therefore, such an inconsistent result is perhaps not surprising. It is possible to obtain effective temperature estimates in better agreement with observation if actual model atmospheres are used; however, soft X-ray opacities are quite sensitive to helium and metal abundances; so that even these results remain model-dependent. Such analysis will be discussed in more detail elsewhere.

The detection of soft X-ray pulsations in PG 1159−035 is, to our knowledge, the first observation of stellar atmospheric pulsational phenomena at these wavelengths. The joint analysis of pulsations as seen in both the X-ray and optical, together with their relative phases and their light curves should provide important new insights into the atmospheres of these objects.

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REFERENCES

de Korte, P. A. J., *et al.* 1981, *Space Sci. Rev.*, **80**, 495.
Grauer, A. D., and Bond, H. E. 1981, *Pub. A.S.P.*, **93**, 388.
Kepler, S. O., Winget, D. E., Grauer, A. D., Cropper, M., O'Donoghue, D., Holberg, J. B., and Barstow, M. 1986, in preparation.
McGraw, J. T., Starrfield, S. G., Liebert, J., and Green, R. 1979, in *IAU Colloquium 53, White Dwarfs and Variable Degenerate Stars*, ed. H. M. Van Horn and V. Wiedemann (Rochester: University of Rochester Press), p. 377.
Shipman, H. L. 1979, in *IAU Colloquium 53, White Dwarfs and Variable Degenerate Stars*, ed. H. M. Van Horn and V. Weidemann (Rochester: University of Rochester Press), p. 86.
Sion, E. M., Liebert, J., and Starrfield, S. G. 1985, *Ap. J.*, **292**, 471.
Vedder, P. W., and Clarke, G. W. 1984, *Bull. AAS*, **14**, 915.
Wesemael, F., Green, R. F., and Liebert, J. 1985, *Ap. J. Suppl.*, **58**, 379.
Winget, D. E., Kepler, S. O., Robinson, E. L., Nather, R. E., and O'Donoghue, D. 1985, *Ap. J.*, **292**, 606.

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